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Tensile Recovery Behavior of Textile Fibers

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Abstract

The recovery data available on textile materials are scarce and difficult to compare. Very few data on fibers have been presented in which differentiation is made between immediate and delayed recovery. Until the present, no adequate method except the pulse-propagation technique has been known to separate these strain components. Using the Instron tensile tester, a cycling method was developed to measure directly the total elongation and permanent set and to permit also determination of the immediate and delayed recovery. The conditions of the tests were standardized. Some studies were made on the effect of deviations from the standardized conditions.

The recovery behavior of 25 samples representing 16 different textile fibers was measured under the standardized conditions. Their recovery behavior is presented by tabular data and by two series of rectangular graphs. The values of immediate and delayed recovery and of permanent set as obtained describe the recovery behavior of fibers with adequate accuracy from the initial application of stress to the breaking point. The recovery behavior was found to be characteristic for any material; however, it was affected by the history of the samples. The recovery of Fiberglas, cotton, Saran, viscose, acetate, nylon, Orlon acrylic fiber, Fiber V, Vinyon CF-HST, N, NOZZ, NORU, wool, casein, and polyethylene is discussed, and an attempt is made to interpret the data.

Results obtained in this study have been correlated to known recovery data of other authors: Meredith, Maillard and coworkers, and Hamburger.

I. Introduction

This report presents an account of systematic investigations of the stress-strain properties of textile fibers with respect to their recovery behavior.

The stress-strain curve can be used to obtain data on such tensile properties as: breaking tenacity, total elongation at break, the relationship between load and elongation at any given stress or strain value, the yield point or elastic limit, the initial modulus of elasticity (elastic stiffness), and the energy required to rupture (toughness) [34]. Conventional stress-strain curves, however, do not provide information on recovery, an important and fundamental fiber characteristic.

Recovery of stretched fibers is their capacity to return to their original length when extended and then released. Some of the elongation is recoverable immediately, some recovers after a longer time, and some remains permanently. These three components of the total elongation have been termed "immediate elastic recovery," corresponding to perfect elasticity; "delayed recovery," or "primary creep;" and "permanent set," or "secondary creep." Actual as well as relative values of the three elongation components are different in various fibers and are influenced by the stress or strain applied and also by time, temperature, humidity, etc.

Elongation components are related to complex phenomena of textiles which are important from a practical standpoint. Generally, a high level of recoverable elongation is desirable for textile fibers, as are also, in most cases, high tenacity, considerable extensibility, and elastic stiffness. A high proportion of immediate elastic recovery is known to contribute to resilience [7], which, according to Mark [28] and Dillon [15], is a combination of stiffness and fast recovery; to crease-resistance [16] and wrinkle-resistance [18]; to softness of fabrics; to fatigue and wear-resistance; and even to comfort. Cassie [12] emphasized that high accessibility of fiber surface to air is an important factor for warmth of textiles and this is best realized in fibers of high recovery. Delayed recovery is also desirable—however, to a lesser extent. In fact, too high a value may be disadvantageous for special purposes. Delayed recovery frequently causes "relaxation shrink-

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age" in woolen fabrics, creating problems in the tailoring of garments [35]. High permanent set is generally undesirable in textile fibers except in isolated instances. It is known that permanent set can be partly recovered by increasing temperature, humidity, and by permutoid swelling, thus affecting dimensional stability [35]. The value of recovery for a specific use depends on the absolute and relative magnitude of the strain components, and the end-use of a fabric will dictate which of these is of particular interest.

Available data on recovery are sparse, frequently incomplete, and difficult to compare. The best collections of fiber properties—the tables on fibers published in *Industrial and Engineering Chemistry* (1948) [11], *Textile World's* "Synthetic Fiber Table" (1949) [6], and the excellent "Fiber Properties Chart" in *Modern Plastics Encyclopedia* (1950) [38]—contain only a few data on "elastic recovery" or "recovery from strain." Present A.S.T.M. Standards [1] on textile materials do not describe test methods for measuring the recovery of filaments. The German Standard Testing Method provides for the measurement of recoverable and nonrecoverable strain in fibers and yarns [17]; the "degree of elasticity" thus obtained is based on the sum of immediate elastic recovery and delayed recovery. It is common practice in Europe to separate permanent set from recoverable elongation without differentiation between immediate and delayed recovery. Notable contributions to recovery data have been furnished by Meredith [30] in England, and Maillard and coworkers [26, 27] in France. They investigated a wide range of textile fibers using the repeated-cycling technique. Meredith's studies were made on a Cliff-type tester with constant rate of loading using a slight modification of the German Standards. He determined the above-mentioned "degree of elasticity" or "elastic recovery" (ratio of recoverable elongation to total elongation) of many single fibers for different loading steps along the stress-strain curve. Maillard and coworkers used the micro machine of Chevenard at constant rate of elongation for a few single fibers and multifilaments. However, neither of these investigators differentiated between immediate elastic recovery and delayed recovery.

When fibers have been extended and released they are known to recover not only to different extents, but also at different rates of speed. The recovery can therefore be better characterized if differentiation is made between that which is immediate and that which is delayed. The importance of the relationship between recovery and time has been recognized even though no satisfactory experimental method existed for measuring it. Needed information on recovery was obtained first by empirical trials which were subject to individual errors and which proved inadequate for quantitative evaluation. Leaderman [25] investigated thoroughly the time factor in recovery and distinguished between "instantaneous elastic deformation" and "delayed deformation." He also published some data on delayed deformation and on delayed recovery for different fibers using long-duration tests. Hoffman [22] discussed the influence of time and described different kinds of "resilience," also indicating some possibilities for measuring the speed of recovery. Hoffman's four types of "resiliency," represented by such materials as quartz, rubber, wool, and "uncross-linked wool," are based on marked differences in the time necessary for recovery and in the modulus of elasticity. Hamburger [20, 21] emphasized the necessity for determining immediate and delayed recovery separately and quantitatively. Taking advantage of the sonic-modulus technique he used a pulse-propagation meter in connection with the Scott IP-2 constant rate of load testing machine for measuring the deflection components. He determined the "immediate elastic deflection," the "primary creep," and the "secondary creep" of viscose acetate and nylon multifilament on the first loading and unloading cycle and also after repeated stresses. Hamburger's investigation must be considered as the first major step in obtaining comparable data on all three elongation components. The significance of this pioneer work cannot be overlooked.

The tensile behavior of visco-elastic materials is different from the relatively simple performance of such ideal solids as crystalline materials since it is strongly dependent upon the length of time the strains or stresses are applied.

The reason for the differentiation between the three components of the total elongation, especially the separation of immediate and delayed recovery, is mainly a practical one. It is significant to know not only to what extent, but also with what speed, an imposed elongation recovers since some elongated fibers "snap back" and others "creep back" after the tension is released.

Immediate elastic recovery is associated with displacement of atoms or molecules from their positions of equilibrium and with their spontaneous and immediate return when the stretching force is removed. According to present theories, immediate elastic recovery of visco-elastic materials occurs mainly in the amorphous region. This recovery is predominant below the yield point at low stresses and strains. Such recovery is possible when a sufficient number of strong cross-linkages are present to prevent the long-chain molecules from sliding over each other, thus facilitating the return of the deformed structures to their original arrangement. Immediate elastic recovery can also result from the straightening of flexible long-chain molecules or from the unfolding of folded molecules.

Permanent set is a result of the irreversible displacement of molecules, and is associated in visco-elastic materials with one of the following processes: (1) slippage of long-chain molecules, or parts of them, along each other due to the breakdown of the secondary bonds, a process generally accompanied by the formation of cracks and by an opening of the structure; (2) alignment of linear chain molecules by tensile stress, observable in x-ray diffraction patterns and also in electron micrographs of high polymers; (3) stabilization of molecular rearrangements obtained during the stretching process by the formation of new cross-linkages between chain molecules, resulting in a "permanent" elongation which remains after releasing the force since the structural rearrangements attained represent new positions of equilibrium. Permanent set may be present to a limited extent even at extremely low stresses, but it is most easily detected after the elastic limit is exceeded. Slippage and orientation increase with progressively higher strains and they prevail near the breaking point. Although permanent set is irreversible, in general, heat or liquids may remove it, thus causing a shrinkage of the material.

Delayed recovery is best described as a hindered elastic recovery since some displaced molecules continue to return spontaneously for some time after release of the tension. It can thus be considered as an interaction between the mechanism causing immediate elastic recovery and the processes producing permanent set.

Analysis of the total elongation and measurement of the three strain components at any stress or strain value furnish the knowledge necessary for critical evaluation of the inherent tensile properties of fibers. Data of these three strain components characterize without undue complexity the response of fibers to imposed strains and stresses. Meos and coworkers [29] suggested differentiation between five components of the total elongation in a Russian paper dealing with the interpretation of the stress-strain behavior of some typical textile fibers. Measurement of so many components would be too difficult and frequently unnecessary from a practical point of view. In contrast, the present paper describes a method for the measurement of three elongation components using repeated loading and unloading cycles. This technique has been applied in a standardized form to obtain necessary data on the immediate elastic recovery, delayed recovery, and permanent set for a number of fibers.

II. Description of the Technique Used

The elongation components were determined using the Instron tensile tester, Model TT-B * [9]. This versatile apparatus has a weighing system utilizing a bonded-type resistance wire strain gage to motivate the recorder pen. The machine has a wide range of load sensitivities and is operated at a constant rate of elongation (crosshead travel). The moving jaw is mounted on a crosshead which can be driven in either direction at constant speeds to any preselected point. The chart of the recording system is driven synchronously, and therefore its movement is proportional to that of the crosshead. The load-elongation relationship for a test material can be obtained continuously, with a wide variation in load, elongation, and time.

Determination of the three components of total elongation is demonstrated schematically in Figure 1, which was obtained by extending a 100/40/2.5 acetate (No. 16†) multifilament to 15.5%. This elongation corresponds to 75% of that at break, while the corresponding stress is equal to 90% of the breaking tenacity. To obtain the curve AM a specimen of 5 in. (12.7 cm.) gage length was extended first to the selected elongation by moving the pulling jaw of the machine at a rate of 5 in. (12.7 cm.) per min. (*i.e.*, 100% elongation of the speci-

* Manufactured by Instron Engineering Corp., Quincy, Mass.

† The numbers following the samples referred to in this study correspond to those listed in Table II and Figure 7B, in which the characteristics of the samples are shown.

men in 1 min.). The jaw motion was then reversed and the jaw returned to the starting point at the above rate of speed. After this loading and unloading cycle, the specimen was allowed to relax for 5 min. The specimen was then extended again to the same point of elongation in a second loading, *HN*, to measure permanent set. The total elongation is indicated by the distance *AB* for the first loading in Figure 1. The distance *BF* for the recovery curve is equal to *AB*, and the distance *GJ* for second loading is also equal to *AB*. These distances correspond to the preselected 15.5% total elongation. Were it possible to remove the tension imposed in the first cycle at once, or at least at an extremely high speed, the resulting recovery would correspond to the immediate elastic part of the total elongation. As this is not possible with the equipment utilized in the study, it remains to determine the immediate elastic recovery from the recovery curve, *MD*, in the following way: The recovery curve, *MD*, can be considered to have an initial straight portion followed by a more or less curved portion. The length of the linear portion was found to vary widely from material to material and even on the same material when elongated to different degrees. When specimens are unloaded at values below the yield point, the straight portion is large, and relatively small near the breaking point, especially for fibers with high delayed recovery. Figure 2 shows a comparison of the linear portions of the recovery curves for three different materials—polyethylene Type A, Vinyon CF-HST, and Fiberglas (Nos. 25, 15, and 1, respectively)—extended to 31.9%, 17.8%, and 2.1%, corresponding to 63%, 89%, and 91% of their total elongation at break, respectively. These fibers vary widely in their recovery, and also in their extensibility, showing total elongations at break of 50.5%, 20.5%, and 2.3%, respectively. Fiberglas is a very elastic fiber and its immediate elastic recovery is predominant even near the breaking point. The immediate elastic recovery, delayed recovery, and permanent set of Vinyon CF-HST are roughly equal at the elongation shown of 17.8%. Polyethylene A has the highest delayed recovery at the breaking point of all the fibers tested (Table III, column 4, and Table IV, 3a and 3c), and its delayed recovery is predominant at the demonstrated point of 31.9% elongation.

In all cases, the straight portion of the recovery curve indicates a constant relationship between stress and strain corresponding to the Hookean law as a result of the immediate elastic recovery. The deviation from this straight line is caused by the additional delayed recovery. This additional recovery increases during removal of the strain with decreasing stresses and with the time necessary to remove the stress. It thus becomes more marked on the recovery curve as the stretch is removed from the fiber.

The recovery curves of the three samples (Figure 2) reach the line of zero stress after elongations of 21.0%, 9.0%, and 2.0%, respectively, are removed. But these values do not represent the immediately recoverable portion of the total elongation because they contain an additional amount of delayed recovery, which is small for Fiberglas, moderate for Vinyon CF-HST, and large for polyethylene A. Since the recovery curves consist of a straight portion corresponding to the perfect elasticity and an additional curved portion representing the delayed recovery, determination of immediate elastic recovery is possible by extending the linear part of the recovery curve to the line of zero load, thus excluding the delayed recovery. When this is done, the immediate elastic recovery of the three fibers is seen to be 5.0%, 4.3%, and 1.6%, respectively.

The highest practicable jaw speed of the Instron tensile tester was used in these tests to avoid significant errors in the measurement of immediate elastic recovery. Special attention is directed to the inertia of the recording system in the evaluation of the straight portion since it contributes a separate linear part to the curve immediately after reversing the extension. This is easily recognized and is, of course, independent of the material tested; it is disturbing at higher jaw speeds, where an additional limitation occurs through overshooting of the crosshead in reversing its travel. (The complications caused by the inertia of pen response were omitted in the schematic graphs of Figures 1 and 2 in the interest of simplifying the demonstration for a better understanding of the method used.) The jaw speed of 5 in. (12.7 cm.) per min. in these tests represents a compromise between high speed, to eliminate as much delayed recovery as possible, and low speed, to avoid the complications arising from the inertia effect of both the recorder and the crosshead of the Instron tensile tester.

The immediate elastic recovery of the acetate multifilament was obtained similarly in Figure 1 by ex-

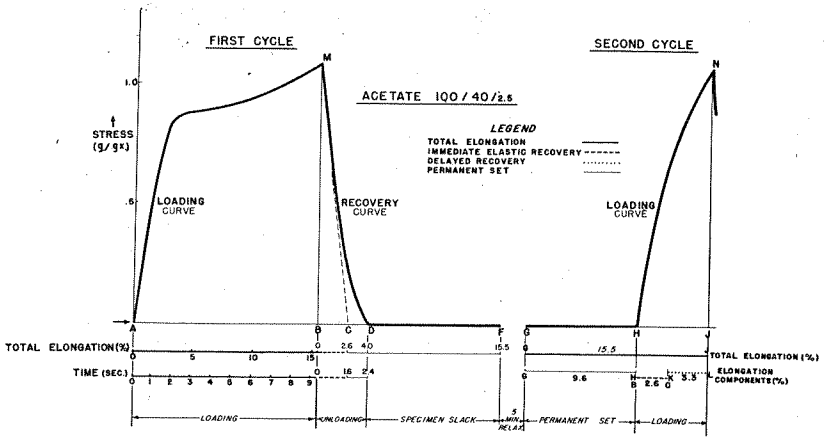


FIG. 1. *Measurement of elongation components.*

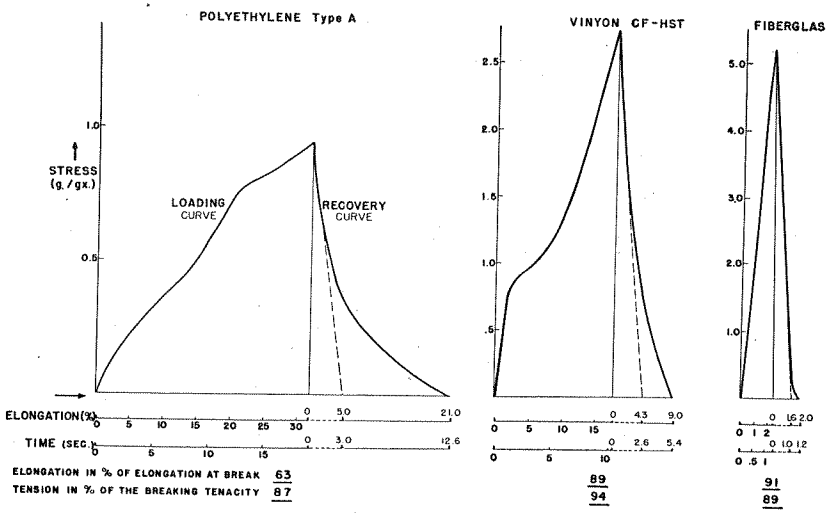


FIG. 2. *Differences in recovery behavior.*

TABLE I. TIME REQUIRED FOR MEASUREMENT OF RECOVERY FOR FIBERS REPORTED IN FIGURES 1 AND 2

1	2	3	4	5	6	7
		Time (sec.) required for:		Immediate elastic recovery in % of initial length	Total elongation:	
Sample No.*	Material	Entire removal of tension	Measurement of immediate elastic recovery		In % of initial length	In % of elongation at break
25	Polyethylene A	12.6	3.0	5.0	31.9	63
15	Vinyon CF-HST	5.4	2.6	4.3	17.8	89
16	Acetate	2.4	1.6	2.6	15.5	75
1	Fiberglas	1.2	1.0	1.6	2.1	91

* Sample numbers correspond to those in Table II and Figure 7B.

tension of the linear part of the first recovery cycle to the line of zero load to point *C*. It is represented by the distance *BC* on the abscissa, corresponding to a value of 2.6% elongation.

It is admitted that this method has the disadvantages of any extrapolation and is subject to error depending upon individual judgment of the linear part. The four materials demonstrated in Figures 1 and 2 show that the graphical evaluation can be considered fairly accurate for Fiberglas, and good for acetate and Vinyon CF-HST, although somewhat uncertain for polyethylene A. Because of the large amount of delayed recovery, more satisfactory results were obtained on polyethylene A at lower elongations, when the removal of stress can be accomplished in a shorter time. The method used was always accurate below the yield point since immediate elastic recovery is preponderant there and the small elongations applied can be removed quickly. The extrapolation procedure could be questioned since the modulus of elasticity has no constant value at different strains for visco-elastic materials and cannot be represented as a straight line. This behavior may produce a slight distortion of the values obtained, especially at higher elongations, but it is not believed to be significant in most cases. Our data of immediate elastic recovery may be higher than the exact values of perfect elastic recovery; however, they could be measured with greater accuracy, permitting a closer approximation of the exact values, if a much higher jaw speed were used for the recovery.

The time required to measure immediate elastic recovery was in the range of from a fraction of a second to a few seconds in the present tests, and was limited mainly by the response of the Instron tensile tester. This time varied for different fibers and for different elongations of the same material, depending, to a great extent, upon the speed and magnitude of the recovery. Occasionally, it was considerably less than the time necessary to remove tension entirely—*e.g.*, for polyethylene A. The data in columns 3 and 4 of Table I demonstrate the different times for polyethylene A, Vinyon CF-HST, acetate, and Fiberglas at relatively high elongations, as represented in Figures 1 and 2. Columns 5, 6, and 7 in Table I contain further data for comparison. The slight variation in time necessary to measure immediate elastic recovery is not serious in view of the large difference between even the longest time of 3 sec. and the time for measurement of delayed recovery, which was always 300 sec.

There is no doubt that the technique described permits approximation of the true values of immediate elastic recovery despite some minor inadequacies. Its application is fully justified by the present lack of a more practicable method to obtain the quantitative data necessary for the recovery characteristics of fibers, except for the pulse-propagation technique.

In contrast to the determination of the immediate elastic recovery, measurement of the nonrecoverable part of the total elongation is quite simple and conclusive. Permanent set was measured after removing the strain and allowing the sample to recover for 5 min. Indication of stress can be seen on the second loading cycle (Figure 1) only after a definite jaw separation is accomplished at point *H* as a result of increased length of the specimen. Therefore, the horizontal part of this curve, *GH*, represents the part of the total elongation not recovered, or the permanent set, which corresponds to 9.6% for the elongation illustrated. Practical considerations dictated selection of the relatively short time of 5 min. for recovery, although measurements of the permanent set might be more desirable after a longer period of recovery, such as 1 hr., or even 1 day. These values would, of course, be lower than those

reported in this paper, but some would not represent the ultimate values since recovery is incomplete even after many hours.

Direct measurement of the delayed recovery is not easily carried out. Calculations can be made readily from the values obtained for total elongation, immediate elastic recovery, and permanent set. By definition, the total elongation (T.E.) is the sum of immediate elastic recovery (I.E.R.), delayed recovery (D.R.), and permanent set (P.S.):

$$\text{T.E.} = \text{I.E.R.} + \text{D.R.} + \text{P.S.}$$

The delayed recovery is therefore obtainable by subtracting the two measured components from the total elongation. In Figure 1 delayed recovery is represented by the distance *KL*, corresponding to 3.3% elongation, since

$$15.5\% - (2.6\% + 9.6\%) = 3.3\%.$$

It is obvious that the data for immediate recovery, delayed recovery, and permanent set obtained by the technique described are dependent upon the conditions of the test. Particular conditions are certainly not essential to secure comparable data so long as they remain the same for all tests and permit measurement in approximate equilibrium. The conditions used in the present tests were standardized on the basis of present practicability; however, they are arbitrary. Other conditions might be more convenient or more desirable in special cases, although the values so obtained would be somewhat different. A lower jaw speed, a delay in releasing the specimen after extension, or a shorter recovery period would decrease the recovery values and increase permanent set. A higher jaw speed would decrease immediate elastic recovery data and increase delayed recovery data. Such changes would also alter the tenacity and the entire stress-strain relationship. Although it might be interesting from a scientific standpoint to obtain information under different test conditions, this was feasible only to a limited degree. In a few instances the test conditions were changed to determine the effect on the data obtained; these changes are described on p. 493.

The measurements, as illustrated by Figure 1, must be repeated at various elongations for any material in order to determine its recovery characteristic at a number of points along the stress-strain curve. Generally, between 10 and 20 different elongations were selected for each fiber at scattered points depending upon its stress-strain behavior. The three strain components were measured or computed from this set of curves for each elongation as indicated. These values were then correlated to the maximal stresses of the first loading cycle, which were expressed according to the recommended practice of the A.S.T.M. in g. per grex [2, 33] on the basis of initial fiber fineness. The grex unit of fineness (weight in g. of 10,000 m.) has many advantages compared to the denier unit (weight in g. of 9,000 m.), which is more commonly used for textiles.* Therefore, such an eminent authority as Smith, in his well-known Edgar Marburg Lecture (1944) [34], strongly recommended that the grex system "be adopted immediately by *all* branches of the textile industry."

There are two procedures for testing the recovery behavior from the initial application of strain up to the breaking point. The first consists of extending a single specimen in successive steps along the curve, starting with the lowest point of elongation practicable, and the second involves the use of a new specimen at each selected point of elongation.

The first method was prescribed by the German Standards [17] and it was practiced by Meredith [30] and Maillard and coworkers [26, 27]. Both methods were investigated early in these studies using acetate multifilaments (No. 16). The results obtained by the two methods were found to be essentially the same. They are demonstrated graphically in Figures 4A, 5A, 5a, and 4B, 5B, 5b, which are described later, on p. 493.

However, it was observed that the method using a single specimen had the following disadvantages: (1) When a single specimen is used, it does not reveal sample variability, which is particularly high in some natural fibers; the use of 10 or 20 specimens allows a closer approach to the average behavior of the material; (2) With a single fiber there is no possibility of returning to lower strain values to obtain supplementary data at points of interest, as the previous stress history of the specimen cannot be eliminated; (3) Fatigue of the single specimen makes measurements near the breaking point difficult and controversial. In view of these

* Tenacity given in g. per grex can be converted into g. per den. by multiplying by 1.11, and, conversely, tenacities in g. per den. multiplied by 0.9 correspond to g. per grex data. Tenacity expressed in g. per grex multiplied by $10d$ gives tensile strength in kg./mm.^{2}, and multiplied by $14{,}223d$ gives tensile strength in p.s.i. (d = density).

disadvantages, a set of new specimens was generally used to determine the recovery behavior of each material. When the specimens were reasonably uniform, it was possible to draw a curve through the somewhat scattered points representing the stresses and total strains in the first loading curve. Where excessive variability occurred, it was necessary to increase the number of specimens tested at each strain value. Although the recorded stress values for a given elongation differed appreciably from one another, only that one was selected for evaluation which did not deviate significantly from the average stress-strain curve, based in most cases on ten individual curves, and the remaining values were discarded. Figure 3 shows this procedure for a wool staple yarn (No. 21) which was extended to 15 different elongations, using 3 specimens for each. From these 45 points only the 15 encircled values next to the average stress-strain curve were used for evaluation. While this procedure was time-consuming, it was considered the only way of securing recovery data representative of the average behavior of an uneven material.

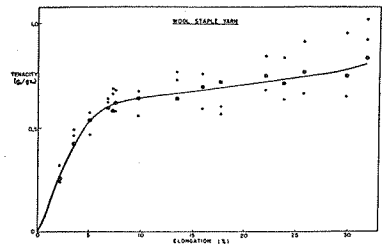


FIG. 3. *Testing procedure for uneven fibers.*

III. Standardized Test Conditions

To obtain comparable and reproducible data on the fibers tested, it was necessary to conduct all tests under the same conditions. The conditions for these recovery tests were standardized as follows:

Gage length	5.0 in. (12.7 cm.)
Rate of elongation	5.0 in. (12.7 cm.) per min.
Removal of elongation	Immediately after extension
Recovery time	5.0 min.
Temperature	70°F (21.1°C)
Relative humidity	65%
Specimens	New fibers for every elongation

IV. Different Methods of Presentation

Typical curves showing the elongation components obtained under the standardized conditions on acetate multifilament 100/40/2.5 (No. 16) are demonstrated in Figure 4A. The tensile stress in g. per grex on the basis of initial fineness is plotted against the total elongation in percent—*i.e.,* increase of length in percent of the initial length. The heavy line is the conventional stress-strain curve, the broken line represents immediate elastic recovery, the dotted line is delayed recovery, and the light line is permanent set. This graph permits determination of the total strain, of that part of the elongation which recovers immediately, of that which recovers in 5 min., and of that which does not recover in 5 min., in percent of initial length at any given stress expressed in g. per grex and at any given strain expressed in percent total elongation. The curves represent average values of the material and were obtained by using 15 different specimens.

The approach of the curves representing total elongation, immediate elastic recovery, and delayed recovery to the zero point was obtained by extrapolation, assuming a linear decrease. The values at the lower elongations (generally less than 2% total elongation, corresponding to an actual elongation of 0.10 in. (0.254 cm.) on the sample tested) are not very accurate and sometimes are considerably scattered. It is difficult to measure such small elongations exactly and to divide them into their components using the described technique. Scattering of points was also frequently observed close to the breaking point. Except for the limitations for these two regions, the reproducibility of the four curves is good when the standard conditions of the tests are carefully observed and the evaluation is made in a uniform manner.

It will be noted in Figure 4A that the total elongation is recoverable below the yield point. Most of the recovery is immediate here and no permanent set appears under the conditions of the test. A marked change in immediate elastic recovery and delayed recovery is noted near the yield point, where considerable increases of strain are accompanied by small increases of stress. The immediate elastic recovery remains nearly constant at higher stresses. The delayed recovery increases rapidly at the yield point until it exceeds the immediate elastic recovery. Above the yield region it does not change appreciably. A crossing of these two curves was found in many fibers tested. In such elastic materials as Fiberglas (No. 1) or Fortisan (No. 4), the immediate elastic recovery remains higher than the delayed recovery up to the breaking point, and no crossing of the two curves appears. It is seen also in Figure 4A that permanent set is observable for the first time at the yield point, and it increases markedly and at an almost constant rate to the breaking point.

This general behavior was found for most of the fibers. However, the absolute values of the strain components, their relationship to the stress or strain applied, and their relative values varied in a very wide range, as will be seen later. Figure 4A, showing the four curves, demonstrates clearly the entire stress-strain and recovery performance of the acetate multifilament but is not suitable for the comparison of a large number of textile materials, especially when the properties are decidedly different.

Therefore, another method was selected to demonstrate the results obtained, which are shown in Figures 5A and 5a as quadratic graphs. The elongation components are expressed as percentages of the actual total elongation on both graphs. They are plotted *vs.* percentage of total elongation at break in 5A, and *vs.* percentage of breaking tenacity in 5a. To demonstrate the entire recovery behavior of a material in relation to strain and stress, two separate quadratic graphs are necessary because of the well-known nonlinear relationship between strain and stress in visco-elastic materials. The recovery data for these graphs are calculated from the original values demonstrated in Figure 4A and are reproduced as curves which divide the quadratic field into three parts, representing the elongation components of the material tested as areas from the beginning of stress and strain to rupture. The two quadratic graphs thus demonstrate the three strain components as percentages of actual total elongation at any strain value, expressed as percent of the total elongation at break, or at any stress value, expressed as percent of the breaking tenacity.

For example, Figure 5A shows that at 20% of the total elongation at break, 65% of the actual elongation recovers immediately, 30% recovers after 5 min., and 5% does not recover. At 50% of the total elongation at break the corresponding values for immediate elastic recovery, delayed recovery, and permanent set are 26%, 32%, and 42%; and at the breaking point, 14%, 16%, and 70%, respectively. When the actual total elongation at break is known (20.5% in this case; see Table II, column 8), the percentage values along the ordinate of the quadratic graph can be readily converted to actual values (*e.g.,* 20% of the total elongation at break of this acetate multifilament is 4.1% elongation, 50% is 10.3%, and 100% is 20.5%).

It can be recognized in Figure 5a also that at 80% of the breaking tenacity, 26% of the actual elongation recovers immediately, 32% recovers after 5 min., and 42% does not recover. In comparing Figures 5A and 5a it can be seen that for this sample, 80% of the breaking tenacity is identical to 50% of the elongation at break. It corresponds also to an actual tenacity of 0.98 g. per grex, which is approximately midway between points 11 and 12 on the stress-strain curve of Figure 4A.

The general comments made above in the discussion of Figure 4A are also apparent from both quadratic graphs 5A and 5a. At lower strains and at lower stresses, the predominant part of the total elongation is immediately recoverable and there is no permanent set. The percentage of immediate elastic recovery and delayed recovery is represented at very low stresses and strains by constant values, corresponding to the previous assumption of the linear increase of immediate elastic recovery and delayed recovery in the beginning of the stretching process. The percentage of immediate elastic recovery decreases above the yield point markedly first, and later at a slower rate. The percentage of delayed recovery does not show large variability, and remains nearly the same from the beginning up to the breaking point. The permanent set starts at 15% of the elongation at break and at 68% of the tenacity at break, which corresponds to 3.1% actual elongation, 0.83 g. per grex actual tenacity, and to the yield point in Figure 4A. The nonrecoverable part of the elongation increases steadily with increasing strain or stress and is predominant near the breaking point.

This demonstration by two quadratic graphs showing the elongation components as areas permits an easy comparison of different fibers. The recovery behavior is presented for different fibers, or for a given material tested under different conditions, always by quadrates of the same size, which can be easily compared. However, this demonstration has three disadvantages: (1) it does not show the actual values of strain, stress, and of strain components,

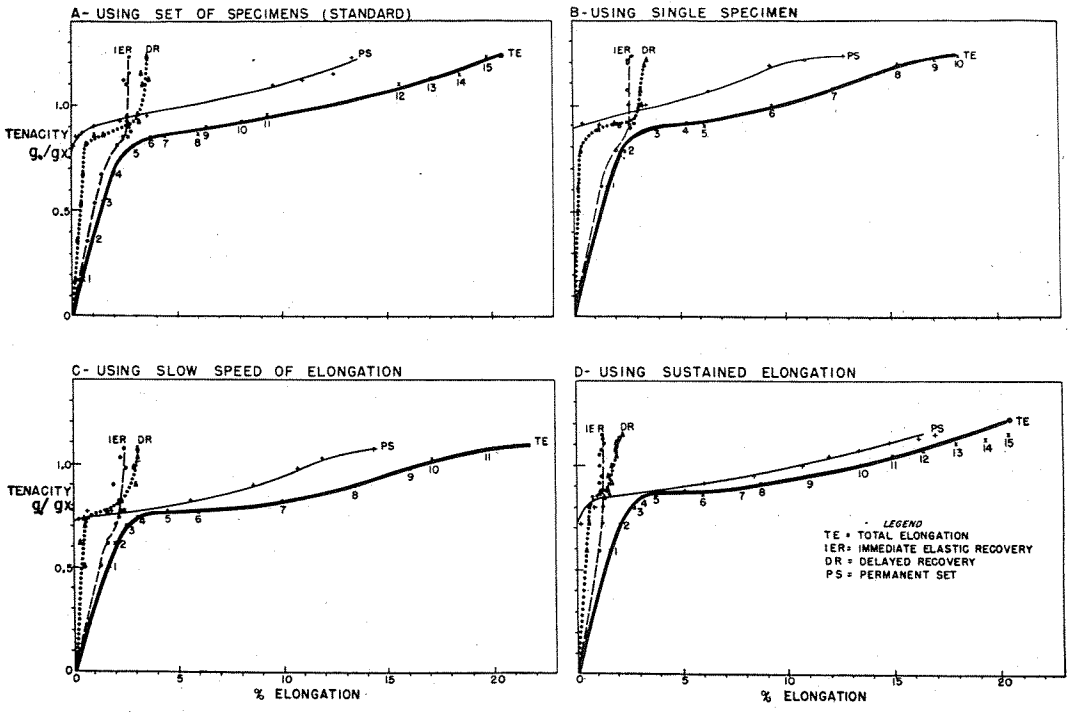


FIG. 4. *Stress-strain curves showing elongation components of acetate multifilament 100/40/2.5.*

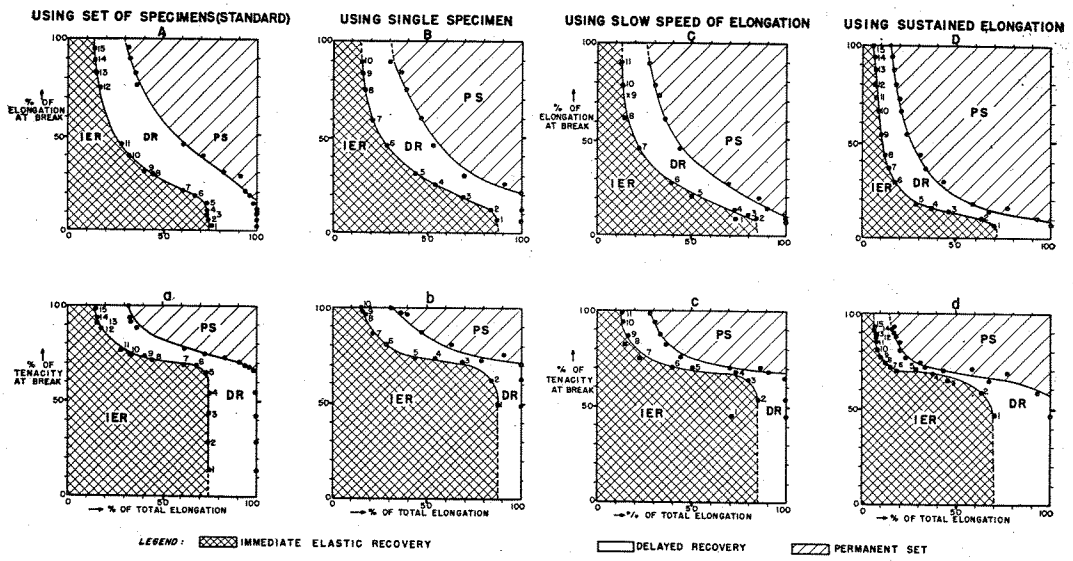


FIG. 5. *Quadratic graphs showing elongation components of acetate multifilament 100/40/2.5.* A, B, C, *and* D *are plotted* vs. *percentage of elongation at break.* a, b, c, *and* d *are plotted* vs. *percentage of tenacity at break.*

which are often required; (2) it does not show the form of the stress-strain curve which is typical for any fiber; and (3) a classification of different materials on the basis of one characteristic property cannot be easily accomplished. The previous demonstration of recovery data with four curves, as illustrated in Figure 4A, does not have these disadvantages; therefore, both methods have been applied in Figures 4A to 4D, 5A to 5D, and 5a to 5d, respectively, to demonstrate the recovery behavior of the same acetate multifilament observed under slight modification of the test conditions. Comparison and discussion of the final data obtained in this study, however, are not presented either by means of four curves or by two quadratic graphs. Instead, a tabular presentation of numerical data and an illustration by two rectangular graphs for each fiber are used. This demonstration is similar to the quadratic graphs but is free of some of their disadvantages. Both the tabular presentation and the rectangular graphs are described in Section VII in more detail.

V. Influence of Test Conditions

The results obtained using only one specimen of the acetate multifilament are demonstrated in Figures 4B, 5B, and 5b. Comparison of these graphs with Figures 4A, 5A, and 5a obtained under the standardized conditions demonstrates that recovery data are essentially the same whether a single specimen or a set of 15 specimens is used. Minor differences observed can be attributed to variability within the sample.

Figures 4C, 5C, and 5c illustrate the recovery of the acetate sample when extended at a speed one-tenth of that prescribed by the standardized conditions—*i.e.*, 0.5 in. (1.27 cm.) per min., or 10% elongation of the specimen per min. Figures 4D, 5D, and 5d show the results at the normal speed, where the elongation was sustained for 5 min. at the maximal value of the first loading cycle instead of being released immediately. Both investigations were carried out using a set of samples; thus, only one of the standardized conditions was changed in each case. A comparison of these six graphs with the three graphs obtained under standardized conditions (Figures 4A, 5A, and 5a) shows clearly that the permanent set was somewhat increased when the lower jaw speed was used, and it was considerably increased at sustained extensions. Thus, the recovery in both cases was decreased as expected. These changes are best observable on the quadratic graphs. The general trend of the curves remained, however, the same and no other significant change in the recovery behavior is observable, except for the lower immediate elastic recovery and higher permanent set after sustained elongation in Figures 4D, 5D, and 5d. These changes are results of sustained elongation, which has a similar effect on the fiber properties as does repeated stress or mechanical conditioning.

The graphs discussed above illustrate not only the different methods of demonstration and the extent to which the recovery data can be altered by variation of the test conditions, but they indicate also the applicability of the technique described. Although the recovery values will be changed as a result of modifications in the test conditions, they can be correlated easily to data obtained under standardized conditions when the changes made and their influence on the recovery are known.

VI. Materials Tested

Most of the tests were made on multifilaments of relatively simple construction. It is known that the properties of these yarns correspond in general to those of the base fibers [31].

An attempt was made to conduct all the tests on fiber materials in the same form—namely, 111-grex (100 den.) multifilament with low twist. However, only a limited number of samples were available in this form, many of them deviating in one respect or another. In some cases it was necessary to use single fibers or staple yarns.

It was the goal of this investigation to obtain information on most of the important textile fibers as well as on materials which represent a wide range of properties. The variety of the samples tested is demonstrated best by the 25 stress-strain curves shown in Figure 6. Among the filaments were strong and weak samples; those with high, medium, and low extensibility; natural, regenerated, and synthetic fibers of nearly every type, including the well-known fibers and some relatively new materials.

Many samples are commercially available but a few were experimental. It is recognized that no single specimen of a given fiber material can be taken as representative of all types of that material. The samples were tested as received, without pretreatment to release any strains developed during the manufacturing process.

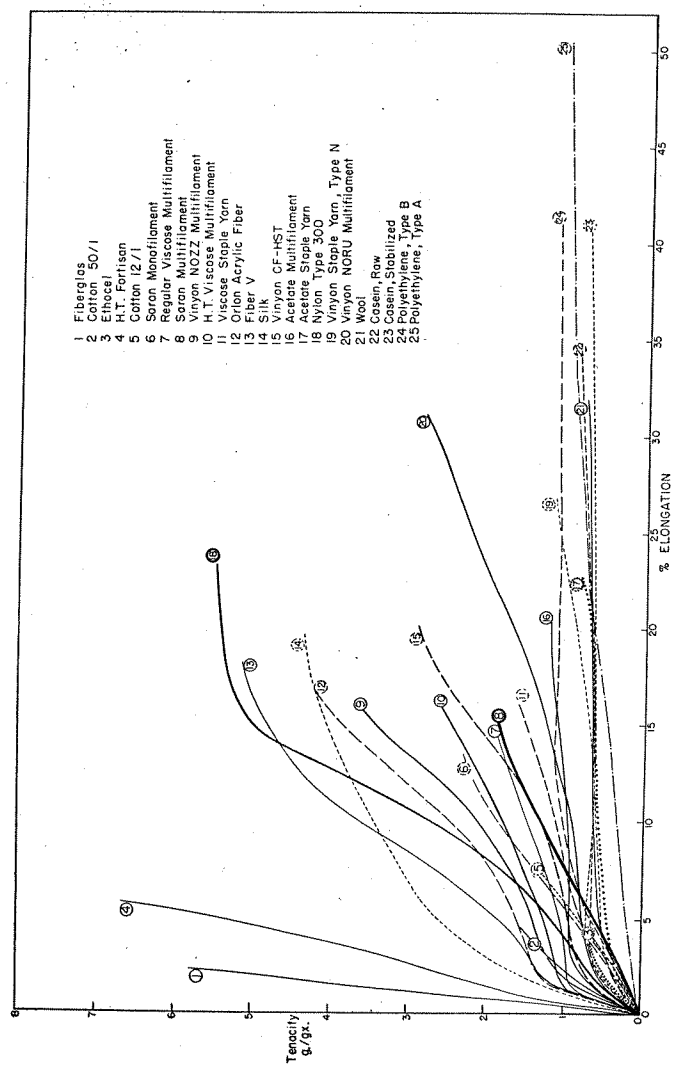


FIG. 6. *Stress-strain curves of fibers tested.*

TABLE II. DATA ON TENSILE PROPERTIES AND

1	2	3	4	5	6	7	8
Sample No.	Material	Source*	Characteristic and designation	Remarks†	Actual fineness (grex)	Breaking tenacity (g./grex)	Total elongation at break (%)
1	Fiberglas ECD	1	Multifilament 900-1/2		114	5.81	2.3
2	Cotton	2	Staple yarn 50/1	1	118	1.56	4.6
3	Ethocel	3	Multifilament 500/100/0	2	642	0.66	5.0
4	High-tenacity Fortisan	4	Multifilament 90/120/3		100	6.68	5.8
5	Cotton		Staple yarn 12/1	3	585	1.37	7.9
6	Saran	5	Monofilament 5 mils diam.	4	209	2.32	13.4
7	Regular viscose	6	Multifilament 100/40		111	1.89	14.7
8	Saran	5	Multifilament 200/12/5z	4	222	1.91	15.5
9	Vinyon NOZZ	7	Multifilament 80/40/5z	5, 6	89	3.60	15.7
10	High-tenacity viscose	6	Multifilament 100/40		111	2.51	15.8
11	Viscose		Staple yarn 20/1	7	296	1.61	16.0
12	Orlon acyrlic fiber	8	Multifilament 100/40/z	2, 8	111	4.19	16.6
13	Fiber V	8	Multifilament 100/40	2, 9	111	5.17	18.2
14	Silk	9	Multifilament 100/132		117	4.39	19.9
15	Vinyon CF-HST	6	Multifilament 80/108/3.5	10	89	2.90	20.0
16	Acetate	8	Multifilament 100/40/2.5		111	1.23	20.5
17	Acetate		Staple yarn 20/1	11	296	0.85	22.8
18	Nylon, Type 300	8	Multifilament 100/40/2.5s		111	5.52	23.3
19	Vinyon N		Staple yarn 20/1	5, 12	296	1.14	26.8
20	Vinyon NORU	7	Multifilament 100/60	5, 13	111	2.85	31.1
21	Wool	10	Worsted staple yarn 28.4/1	14	314	0.81	31.9
22	Casein, raw	11	Multifilament 300/40	2	333	0.91	34.4
23	Casein, stabilized	11	Multifilament 300/40	2, 15	333	0.83	40.8
24	Polyethylene, Type B	6	Monofilament 12 mils diam.	2, 16	684	1.17	41.3
25	Polyethylene, Type A	6	Monofilament 12 mils diam.	2, 17	684	1.08	50.5

* Source:
1. Owens-Corning Fiberglas Corp., Toledo, Ohio
2. Standard Coosa-Thatcher Co., Chattanooga, Tenn.
3. The Dow Chemical Co., Midland, Mich.
4. Celanese Corp. of America, New York, N. Y.
5. The Saran Yarns Co., Odenton, Md.
6. American Viscose Corp., Marcus Hook, Pa.
7. Carbide & Carbon Chemicals Corp., S. Charleston, W. Va.
8. E. I. du Pont de Nemours & Co., Inc., Wilmington, Del.
9. Belding-Heminway Co., Inc., New York, N. Y.
10. Forstmann Woolen Co., Passaic, N. J.
11. Eastern Regional Research Laboratory, Philadelphia, Pa.

† Remarks:
1. Staple: 1½ in. (2.86 cm.), 22.7 t.p.i. (8.9 t.p.cm.)
2. Experimental sample
3. Staple: 1 7/8 in. (2.72 cm.), 11.6 t.p.i. (4.6 t.p.cm.)
4. Polyvinylidene chloride
5. Copolymer of vinyl chloride and acrylonitrile (40%)
6. Oriented stretched 1300%
7. Staple: 2 in. (5.08 cm.), 3.3 grex.
8. Polyacrylonitrile
9. Polyethylene glycol terephthalate
10. Copolymer of vinyl chloride and vinyl acetate (10%)
11. Staple: 1½ in. (3.81 cm.), 3.3 grex
12. Staple: 1½ in. (3.81 cm.), 3.5 grex
13. Oriented stretched 1300%, reacted without tension 135°C
14. Staple: 2.9 in. (7.37 cm.), U. S. 64's, 20.9 t.p.i. (8.2 t.p.cm.)
15. Formaldehyde-treated
16. Cold-drawn not relaxed, highly oriented
17. Cold-drawn and relaxed, medium oriented

VII. Presentation of Recovery Data

A tabular presentation of numerical data is the simplest, although not the best, presentation of recovery behavior. Table II shows the fibers tested in order of increasing extensibility, with information on their source, fineness, breaking tenacity, elongation at break, recovery. The list contains 25 individual samples of 16 different materials. The immediate elastic recovery, delayed recovery, and permanent set are expressed as percentages of the actual total elongation at the mid-points of the stress-strain curve (at 50% of the breaking tenacity in column 9 and at 50% of the total elongation at break in column 10) and at the breaking point (column 11). Although the recovery behavior of fibers cannot be characterized fully by numerical values at only three

ELONGATION COMPONENTS OF FIBERS TESTED

9			10			11			12
			Elongation components in % of actual total elongation:						
At 50% of breaking tenacity			At 50% of elongation at break			At the breaking point			
Immediate elastic recovery	Delayed recovery	Permanent set	Immediate elastic recovery	Delayed recovery	Permanent set	Immediate elastic recovery	Delayed recovery	Permanent set	Sample No.
78	19	3	78	19	3	72	22	6	1
63	35	2	60	34	6	44	32	24	2
71	29	0	80	18	2	50	36	14	3
50	34	16	48	37	15	44	28	28	4
34	44	22	36	46	18	26	30	44	5
53	47	0	53	47	0	42	58	0	6
50	42	8	26	27	47	19	20	61	7
56	44	0	54	46	0	33	54	13	8
39	49	12	40	48	12	26	44	32	9
28	38	34	23	32	45	18	21	61	10
28	32	40	24	30	46	16	22	62	11
30	47	23	30	45	25	21	37	42	12
33	52	15	28	50	22	18	37	45	13
47	42	11	25	33	42	16	20	64	14
27	51	22	30	48	22	25	46	29	15
74	26	0	26	32	42	14	16	70	16
58	42	0	23	25	52	12	18	70	17
29	67	4	27	67	6	18	54	28	18
32	68	0	22	40	38	12	30	58	19
17	39	44	21	41	38	12	28	60	20
64	34	2	28	50	22	16	44	40	21
88	12	0	22	40	38	14	29	57	22
77	23	0	20	30	50	12	28	60	23
76	24	0	22	58	20	10	30	60	24
35	58	7	20	64	16	10	49	41	25

selected points, it is believed that this tabular presentation demonstrates the recovery fairly well for comparative purposes and for general discussion. A few of the values in column 9 are, however, subject to marked errors arising from the uncertainty of measurements at low elongations.

Since it is necessary to know the recovery from the beginning of the stretching up to rupture, the results obtained in this study are also illustrated in Figure 7B by means of two sets of rectangular graphs which represent the entire recovery behavior of the 25 individual samples tested. This demonstration is similar to that illustrated in Figures 5A and 5a by two quadrates, but is free of some of its disadvantages. In both types of graphs data for immediate elastic recovery, delayed recovery, and permanent set are plotted as percentages of the actual total elongation along the abscissa. However, in the rectangular graphs they are plotted against total elongation expressed as percent of original length (in the upper set) and against tenacity expressed as grams per grex (in the lower set). The height of the rectangular graphs represents the extensibility in the upper set and the tenacity at break in the lower set. The samples are arranged in order of increasing extensibility, and their numbers correspond to the sample numbers in Table II. Each rectangular graph is divided into three areas, depicting the immediate elastic recovery, delayed recovery, and permanent set, except the two graphs of Saran monofilament (No. 6), where no permanent set was observed.

The recovery behavior of the acetate multifilament, demonstrated by four curves in Figure 4A and by two quadrates in Figures 5A and 5a, is also demonstrated by two rectangular graphs in Figures 7A and 7a. It can be seen directly from Figure 7A that when this filament is extended to 15%, only 18% of this actual elongation recovers immediately, 23% recovers in 5 min., and 59% does not recover. The actual values for immediate elastic recovery, delayed recovery, and permanent set are 2.7%, 3.5%, and

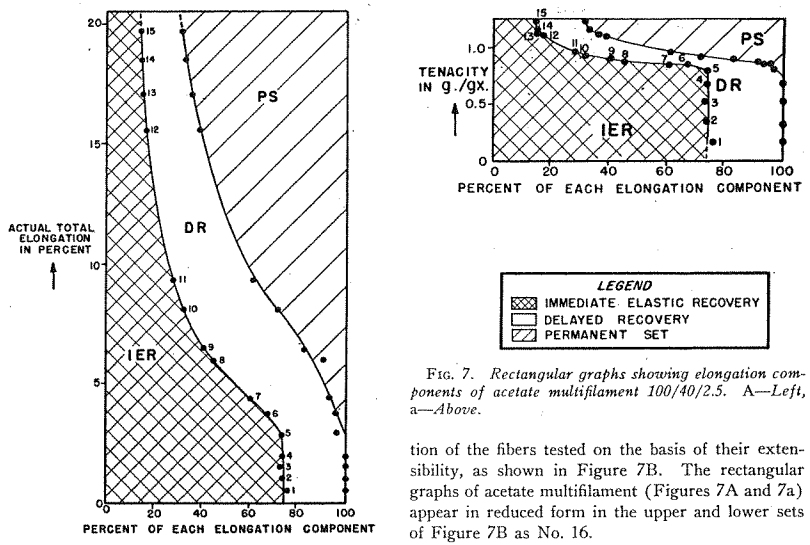


FIG. 7. *Rectangular graphs showing elongation components of acetate multifilament 100/40/2.5.* A—*Left,* a—*Above.*

8.8% elongation, respectively, since the actual total elongation here is 15%. The preponderant portion of the elongation is thus nonrecoverable at this point, with the recovery divided almost evenly between immediate and delayed. Similar information is provided at a given stress value in Figure 7a. It shows that at a stress of 0.90 g. per grex, the values for immediate elastic recovery, delayed recovery, and permanent set are 41%, 42%, and 17%, respectively, of the actual total elongation at this stress value. Since the elongation at a stress of 0.90 g. per grex is shown to be 6.4% on the stress-strain curve of the fiber (Figure 4A), the actual values for immediate elastic recovery, delayed recovery, and permanent set are 2.6%, 2.7%, and 1.1%, respectively. This demonstration by rectangular graphs permits immediate determination of the three strain components as percentages of the actual total elongation for any elongation given in percent and for any tensile stress expressed in g. per grex. Also, actual values of the three components can be computed for any stress and strain from these data when the stress-strain curve is known. In addition, the rectangular graphs facilitate comparison and classification of the fibers tested on the basis of their extensibility, as shown in Figure 7B. The rectangular graphs of acetate multifilament (Figures 7A and 7a) appear in reduced form in the upper and lower sets of Figure 7B as No. 16.

Description and discussion of the results obtained will not be restricted to the relative values of recovery as given in Table II and Figure 7B. They will also cover actual values of the elongation components for the convenience of those who prefer such data.

VIII. Results

A. General

The extensibility of the fibers tested varies from 2.3% for Fiberglas (No. 1) to 50.5% for polyethylene A (No. 25), and the tenacity varies from 0.66 g. per grex for Ethocel (No. 3) to 6.68 g. per grex for high-tenacity Fortisan (No. 4). A comparison of the upper set with the lower set in Figure 7B illustrates the well-known fact that highly extensible fibers have low tenacities in most cases, but that poor extensibility is not always connected with high tenacity. Broadly, the rectangular graphs of the two sets shows some similarity of pattern, although marked differences exist among the fibers tested. The similarity might be considered as a result of their common structure since all of them, except Fiberglas, consist of long-chain molecules.

FIGURE 7B. RECTANGULAR GRAPHS SHOWING RECOVERY BEHAVIOR OF FIB

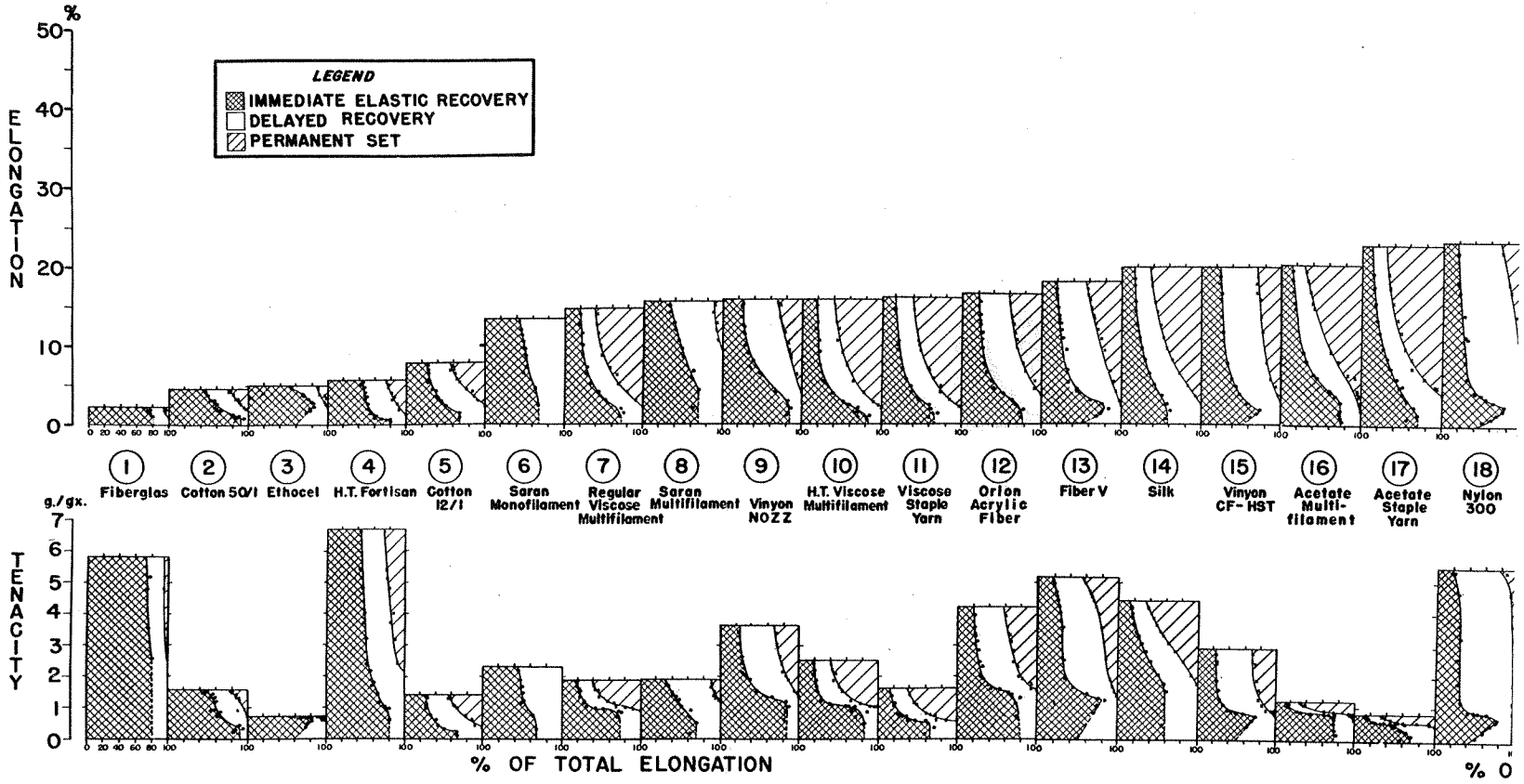
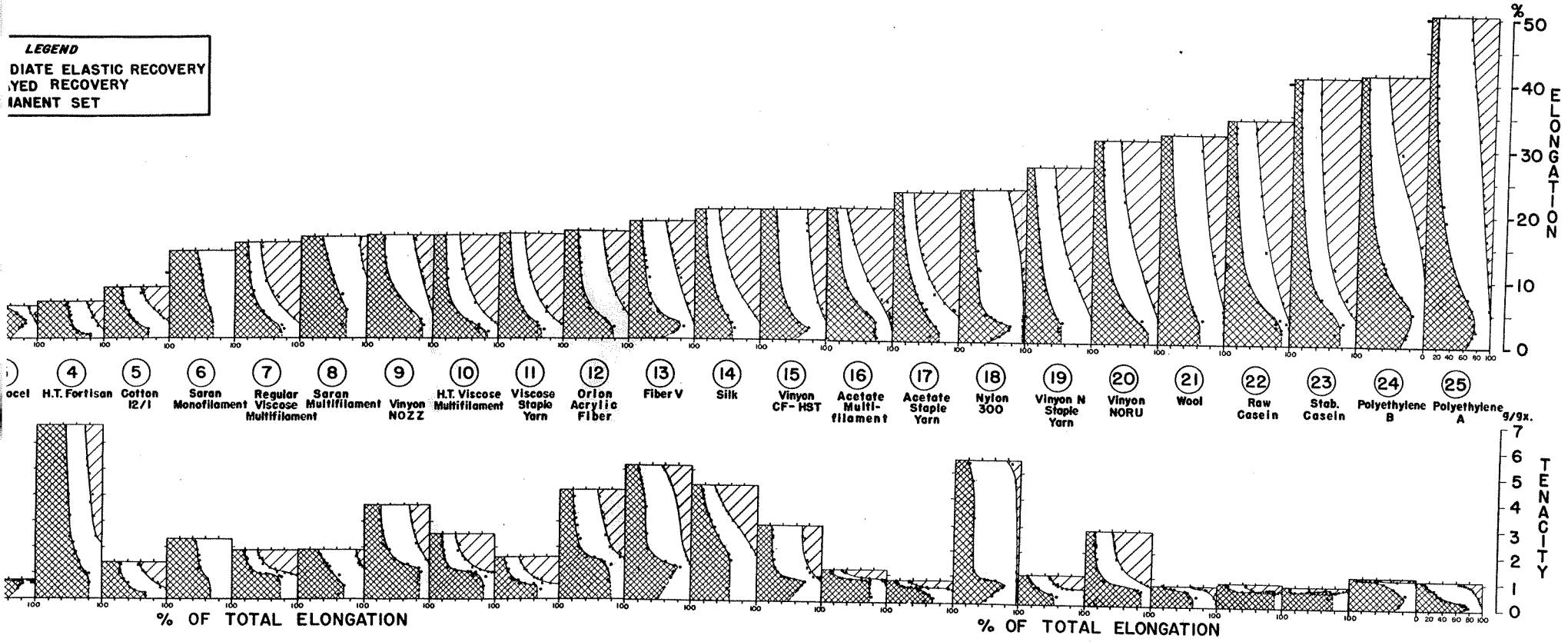


FIGURE 7B. RECTANGULAR GRAPHS SHOWING RECOVERY BEHAVIOR OF FIBERS TESTED



Their common properties make possible their practical use as textile materials in spite of marked differences in chemical composition and structural details.

The rectangular graphs in Figure 7B clearly demonstrate that recovery at low stresses and strains is complete in every case under the conditions of these tests. The limit for this behavior is about 1% total elongation for Fortisan (No. 4), 2% for viscose (No. 7, 10, 11), 3% for acetate (No. 16), 4% for Vinyon NORU (No. 20), 6% for wool (No. 21), and 11% for polyethylene B (No. 24). This limit corresponds to the yield point where elongation with increasing stress begins to increase rapidly. It is observable on the stress-strain curves as well as on both rectangular graphs, where it is indicated by the beginning of permanent set.

B. Immediate Elastic Recovery

The immediate elastic recovery shows a wide variation at different values of strain and stress for most fibers (Figure 7B). It is always predominant at low elongations and constant values are demonstrated up to the yield point for many fibers according to the previously discussed linear increase of immediate elastic recovery and delayed recovery at very low elongations (Figure 4A). Although this assumption seemed to be justified by the constant relationship between stress and total elongation observable on the conventional stress-strain curves below the yield point, some of the fibers indicated marked deviations from the linearity. Therefore, the validity of our assumption was re-examined on high-tenacity Fortisan (No. 4), acetate multifilament (No. 16), nylon 300 (No. 18), and polyethylene A (No. 25). To obtain more accurate data at low elongations, a longer initial gage length (20.0 in., or 50.8 cm.) was used in these tests. The recovery obtained for Fortisan and acetate indicates a fairly constant relationship between immediate elastic recovery and delayed recovery at the beginning of the stretching process. In contrast to this, a marked increase of immediate elastic recovery at very low stress and strain values was observed for nylon and polyethylene A, as illustrated at the lower parts of the rectangular graphs Nos. 18 and 25. An increase of immediate elastic recovery is demonstrated also for Ethocel (No. 3), Fiber V (No. 13), Vinyon CF-HST (No. 15), and polyethylene B (No. 24). Although a few other fibers indicated some deviation from a constant relationship, no definite conclusion was possible from the tests performed as to whether or not the demonstrated constancy in the lower parts of the rectangular graphs should be changed.

The decrease of immediate elastic recovery is nearly linear between the yield point and rupture only for the highly recoverable fibers—Fiberglas (No. 1), 50/1 cotton (No. 2), Ethocel (No. 3), and Saran (Nos. 6 and 8). For all other fibers immediate elastic recovery decreases with increasing strain and stress first rapidly and then at a slower rate. The immediate elastic recovery is usually low near the breaking point, having values between 10% and 40% of the total elongation in most cases (column 11, Table II). It was found higher than 40% only for such elastic fibers as Saran monofilament (No. 6), high-tenacity Fortisan (No. 4), 50/1 cotton (No. 2), Ethocel (No. 3), and Fiberglas (No. 1). It is of interest to note that these high percentages are connected with relatively low extensibilities, which are between 2.3% and 13.4%. The actual values of immediate elastic recovery at the breaking point are in the range of from 1.6% to 5.8% for the fibers tested (Table IV, 3a), but they do not represent necessarily the maximal values for a given fiber. The highest actual values for immediate elastic recovery at the breaking point were found in Saran monofilament (5.8%), Vinyon CF-HST, wool, and polyethylene A (5.0%), Saran multifilament and stabilized casein (4.9%), raw casein (4.8%), and nylon and polyethylene B (4.2%). These fibers can be considered as the most elastic materials tested when only the actual values for immediate elastic recovery at the breaking point are taken into account and the delayed recovery is disregarded.

C. Permanent Set

The permanent set of the samples tested shows even higher variability than the immediate elastic recovery in its actual value, in relation to the total elongation, and in that point at which it becomes observable. Permanent set generally begins at the yield point, and increases steadily and more or less rapidly up to rupture. The start of permanent set may serve as an indication of the limits of stress and strain if the disadvantages of secondary creep are to be avoided. When the recovery data are plotted against tenacity (lower graphs, Figure 7B), a very rapid increase of permanent set is demon-

Their common properties make possible their practical use as textile materials in spite of marked differences in chemical composition and structural details.

The rectangular graphs in Figure 7B clearly demonstrate that recovery at low stresses and strains is complete in every case under the conditions of these tests. The limit for this behavior is about 1% total elongation for Fortisan (No. 4), 2% for viscose (No. 7, 10, 11), 3% for acetate (No. 16), 4% for Vinyon NORU (No. 20), 6% for wool (No. 21), and 11% for polyethylene B (No. 24). This limit corresponds to the yield point where elongation with increasing stress begins to increase rapidly. It is observable on the stress-strain curves as well as on both rectangular graphs, where it is indicated by the beginning of permanent set.

B. Immediate Elastic Recovery

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The decrease of immediate elastic recovery is nearly linear between the yield point and rupture only for the highly recoverable fibers—Fiberglas (No. 1), 50/1 cotton (No. 2), Ethocel (No. 3), and Saran (Nos. 6 and 8). For all other fibers immediate elastic recovery decreases with increasing strain and stress first rapidly and then at a slower rate. The immediate elastic recovery is usually low near the breaking point, having values between 10% and 40% of the total elongation in most cases (column 11, Table II). It was found higher than 40% only for such elastic fibers as Saran monofilament (No. 6), high-tenacity Fortisan (No. 4), 50/1 cotton (No. 2), Ethocel (No. 3), and Fiberglas (No. 1). It is of interest to note that these high percentages are connected with relatively low extensibilities, which are between 2.3% and 13.4%. The actual values of immediate elastic recovery at the breaking point are in the range of from 1.6% to 5.8% for the fibers tested (Table IV, 3a), but they do not represent necessarily the maximal values for a given fiber. The highest actual values for immediate elastic recovery at the breaking point were found in Saran monofilament (5.8%), Vinyon CF-HST, wool, and polyethylene A (5.0%), Saran multifilament and stabilized casein (4.9%), raw casein (4.8%), and nylon and polyethylene B (4.2%). These fibers can be considered as the most elastic materials tested when only the actual values for immediate elastic recovery at the breaking point are taken into account and the delayed recovery is disregarded.

C. Permanent Set

The permanent set of the samples tested shows even higher variability than the immediate elastic recovery in its actual value, in relation to the total elongation, and in that point at which it becomes observable. Permanent set generally begins at the yield point, and increases steadily and more or less rapidly up to rupture. The start of permanent set may serve as an indication of the limits of stress and strain if the disadvantages of secondary creep are to be avoided. When the recovery data are plotted against tenacity (lower graphs, Figure 7B), a very rapid increase of permanent set is demon-

strated at the yield point for raw and stabilized casein (Nos. 22 and 23) and for polyethylene B (No. 24). The overlapping of the areas for permanent set and immediate elastic recovery in the graphs of the casein samples is due to high plastic flow immediately after the yield point is passed. This is also observable on the conventional stress-strain curves by decreasing tenacities at increasing elongations beyond the yield point. The demonstrated overlapping does not indicate the absence of delayed recovery at any stress values, and can be understood easily by the fact that a given stress corresponds not only to one, but to two or even three different strain values in the critical region near the yield point.

The Saran monofilament (No. 6) was the only fiber evaluated in which no permanent set could be measured under conditions of the test. The nonrecoverable elongation of Fiberglas (No. 1), Saran multifilament (No. 8), and Ethocel (No. 3) is insignificant since it is less than 15% of the total elongation at the breaking point (column 11, Table II). The permanent set of 50/1 and 12/1 cotton, Fortisan, Vinyon NOZZ, Orlon acrylic fiber, Fiber V, Vinyon CF-HST, nylon 300, wool, and polyethylene A is relatively low, in no case exceeding 50% of the total elongation at the breaking point. Many of the fibers tested show a predominance of permanent set (from 50% to 70% of the total elongation) at the breaking point; these include regular and high-tenacity viscose multifilament, viscose staple yarn, silk, acetate multifilament, acetate staple yarn, Vinyon NORU, Vinyon N staple yarn, raw and stabilized casein, and polyethylene B. The actual values of permanent set range from zero for Saran monofilament to 24.8% for polyethylene B at the breaking point (Table IV, 3a).

D. Delayed Recovery

As demonstrated by the rectangular graphs, the percentage of the immediately recoverable and of the nonrecoverable part of the total elongation varies widely from the beginning of extension to the breaking point for any fiber tested. In contrast to this, the percentage of primary creep does not show much variability in Figure 7B and for most fibers it has two distinct values separated from each other near the yield point. These two values remain approximately constant at different stresses and strains, except at the very beginning of the stretching process, where some fibers—*e.g.*, nylon 300 (No. 18) and polyethylene A (No. 25)—show variability in the relationship between immediate elastic recovery and delayed recovery. The percentage of delayed recovery in relation to the total elongation at the breaking point, of course, varies widely from material to material, but still remains between 16% and 58%. It is small (below 25%) for Fiberglas, regular viscose, high-tenacity viscose, viscose staple yarn, natural silk, acetate multifilament and staple yarn; but it is high (above 50%) for Saran monofilament and multifilament and nylon.

The actual values of the delayed recovery at the breaking point are less than 10% for all the fibers tested except for the following highly extensible materials: nylon 300, wool, raw and stabilized casein, and polyethylene A and B. Table III shows actual values of recovery for these 6 fibers, which are listed in order of increasing actual values of permanent set. Beside immediate elastic recovery and delayed recovery, total recovery is also listed (column 5). Total recovery is the sum of immediate elastic recovery and delayed recovery. It corresponds to the recovery data obtained by test methods of the German Standards [17] and to results of other investi-

TABLE III. RECOVERY DATA AT THE BREAKING POINT OF FIBERS WITH HIGH DELAYED RECOVERY

1 Sample No.*	2 Material	3 Immediate elastic recovery	4 Delayed recovery	5 Total recovery (in % of initial length)	6 Permanent set	7 Total elongation
18	Nylon 300	4.2	12.6	16.8	6.5	23.3
21	Wool	5.1	14.0	19.1	12.8	31.9
22	Raw casein	4.8	10.0	14.8	19.6	34.4
25	Polyethylene A	5.1	24.7	29.8	20.7	50.5
24	Polyethylene B	4.2	12.3	16.5	24.8	41.3
23	Stabilized casein	4.9	11.4	16.3	24.5	40.8

* Sample numbers correspond to those in Table II and Figure 7B.

gators who did not separate the two recovery components.

It will be noted that the actual values of immediate elastic recovery in Table III are relatively high, but that those of delayed recovery are markedly higher. The values for immediate elastic recovery, delayed recovery, and total recovery are of the same order of magnitude for the 6 samples, with the exception of the high delayed recovery and high total recovery of polyethylene A. The series can be divided, however, into two groups with respect to permanent set. In the first group are nylon 300 and wool, in which high recovery is accompanied by the desirable property of relatively low permanent set. The second group, consisting of raw and stabilized casein and polyethylene A and B, contains fibers whose high recovery is accompanied by high permanent set, and whose total extensibility is thus considerably increased. Despite their remarkable recovery, these samples cannot be considered extremely elastic (at least not near to rupture) because of their large permanent set values.

E. Range of Recovery Data Observed

The range of tensile properties at the breaking point is shown in Table IV. The data of immediate elastic recovery, delayed recovery, total recovery, and permanent set are presented as actual values (3a) and as relative values (3b and 3c). The relative values of the components are expressed as percentages of the total elongation (3b), corresponding to the presentation in Table II and Figure 7B, and of the total recovery (3c).

It is interesting to compare the small differences in the actual values of immediate elastic recovery (3a, Table IV) with the high variability of the data for delayed recovery, total recovery, and permanent set.

The extremes of the relative values for immediate elastic recovery correlated to total recovery are shown to be 17% and 95% in Table IV, 3c; in most cases, between 25% and 50% of the total recovery is immediate at the breaking point. The high variability of the immediately recoverable portion demonstrates the necessity of separating the total recovery into two components and knowing their relative values for a precise characterization of inherent fiber properties. Although marked differences in the "quality" of recovery (*i.e.*, the speed of recovery) may be observable even by subjective evaluations, it is obvious that smaller differences can be detected only by quantitative measurements of the components.

TABLE IV. EXTREME VALUES OBTAINED ON FIBERS TESTED* FOR TENACITY, EXTENSIBILITY, AND ELONGATION COMPONENTS AT THE BREAKING POINT

	Lowest		Highest	
1. Tenacity (g. per grex)	Ethocel (No. 3)	0.66	Fortisan (No. 4)	6.6
2. Total elongation (%)	Fiberglas (No. 1)	2.3	Polyethylene A (No. 25)	50.5
3. Elongation components				
a. Actual values in % of initial length				
Immediate elastic recovery	Fiberglas (No. 1)	1.6	Saran monofilament (No. 6)	5.8
Delayed recovery	Fiberglas (No. 1)	0.5	Polyethylene A (No. 25)	24.7
Total recovery	Fiberglas (No. 1)	2.1	Polyethylene A (No. 25)	30.5
Permanent set	Saran monofilament (No. 6)	0.0	Polyethylene B (No. 24)	24.8
b. Relative values in % of actual total elongation				
Immediate elastic recovery	Polyethylene A and B (Nos. 24, 25)	10	Fiberglas (No. 1)	72
Delayed recovery	Acetate multifilament (No. 16)	16	Saran monofilament (No. 6)	58
Total recovery	Acetate multifilament (No. 16) and staple yarn (No. 17)	30	Saran monofilament (No. 6)	100
Permanent set	Saran monofilament (No. 6)	0	Acetate multifilament (No. 16) and staple yarn (No. 17)	70
c. Relative values in % of actual total recovery				
Immediate elastic recovery	Polyethylene A (No. 25)	17	Fiberglas (No. 1)	95
Delayed recovery	Fiberglas (No. 1)	5	Polyethylene A (No. 25)	83

* Numbers in parentheses following names of fibers correspond to those given in Table II and Figure 7B.

IX. Discussion of Recovery Behavior of Some Textile Fibers

A. Fiberglas

Fiberglas (No. 1) represents an extreme among the fibers tested. Due to its brittleness, the practical use of Fiberglas as a textile material is limited, despite its high tenacity and its excellent recovery. Its principal limitation is that it is easily damaged in service. The extremely low extensibility and the small amount of permanent set (only 6% of the 2.3% elongation at break) agree well with what one would expect from the atomic structure of silicate glasses, very different from the giant-chain molecular structure of all other textile fibers. According to our present knowledge, silicate glasses are built from a random network of silicon and oxygen atoms. Their arrangement is tetrahedral and the gaps of this structure are filled by the metallic atoms—sodium, potassium, calcium, etc. It is apparent that such a network structure is a strong but very rigid one since no slip planes or long chains are present and no slippage due to breakdown of secondary bonds is possible. Therefore, practically no permanent set is observable as a result of applied strain. The only failure under stress which occurs is rupture of the fibers.

B. Cotton

Comparison of the two cotton staple yarns in Figure 7B shows that the 50/1 yarn (No. 2) has a lower elongation and a slightly higher tenacity than the 12/1 yarn (No. 5). At a given level of strain or stress beyond the yield point, the 50/1 cotton shows a higher recovery than the 12/1 sample. The immediately recoverable part of the 50/1 sample exceeds the delayed recoverable portion, whereas these two components are almost equal in the 12/1 yarn. These differences are also demonstrated by the data of columns 9, 10, and 11 of Table II, where the immediate elastic recovery is seen to be higher and the permanent set lower in the 50/1 yarn than in the 12/1 yarn. For these reasons, the 50/1 yarn can be considered more elastic than the 12/1.

Both yarns were processed from American cotton of similar quality. The cotton fibers and the yarns have the following characteristics:

	50/1 Yarn	12/1 Yarn
Mean staple length (in.)	$1\frac{1}{8}$	$1\frac{1}{16}$
Mean staple length (cm.)	2.86	2.72
Coefficient of length variability (%)	29.4	29.4
Maturity (%)	82	81
Actual fineness (grex)	118	585
Actual fineness (cotton count)	50	10.1
Twist (turns per in.)	22.7	11.6
Twist (turns per cm.)	8.9	4.6
Twist factor: $\frac{\text{turns per in.}}{\sqrt{\text{actual cotton count}}}$	3.21	3.65

The tensile behavior, including the recovery of these staple yarns, is a function of the single fibers as well as of the yarn construction. It is reasonable to assume that their common characteristics, such as low extensibility and tenacity but relatively high recovery, are inherent cotton properties. The recovery is understandable in view of the morphology of the cotton fiber and of the molecular structure of cellulose. Cotton fibers consist of many fibrils, oriented at an acute angle with respect to the fiber axis. In cellulose the lateral forces of attraction between the chain molecules are high due to so-called hydrogen bonds formed by the three hydroxyl groups per anhydroglucose unit. This explains the marked recovery despite the inflexibility of the cellulose molecules. The differences observed between the two yarns might be caused by the differences in fineness and twist factor or by possible processing variations. In any case, the finer 50/1 yarn with the lower twist factor has higher recovery and tenacity but lower extensibility.

C. Saran

The two Saran specimens tested show a behavior similar to the cotton samples. The Saran monofilament (No. 6) has a higher recovery and tenacity but lower extensibility than the Saran multifilament (No. 8). The lower immediate elastic recovery and tenacity, the low permanent set, and, consequently, the somewhat higher extensibility of the multifilament are probably due to a lower orientation, or the presence of plasticizer, or the filament construction.

D. Multifilaments and Staple Yarns of Viscose, Acetate, and Vinyon N

The graphs in Figure 7B and the data in Table II for 3 entirely different samples of viscose (regular and high-tenacity multifilaments and staple yarns,

TABLE V. COMPARISON OF TENSILE PROPERTIES OF ORLON ACRYLIC FIBER, FIBER V, AND NYLON 300 AT THE BREAKING POINT

	Orlon acrylic fiber (No. 12)*	Fiber V (No. 13)*	Nylon 300 (No. 18)*
1. Tenacity (g. per grex)	4.19	5.17	5.52
2. Total elongation (%)	16.6	18.2	23.3
3. Elongation components			
a. Actual values in % of initial length			
Immediate elastic recovery	3.7	3.1	4.2
Delayed recovery	5.9	6.6	12.6
Total recovery	9.6	9.7	16.8
Permanent set	7.0	8.5	6.5
b. Relative values in % of actual total elongation			
Immediate elastic recovery	22	17	18
Delayed recovery	36	36	54
Total recovery	58	53	72
Permanent set	42	47	28
c. Relative values in % of actual total recovery			
Immediate elastic recovery	39	32	25
Delayed recovery	61	68	75

* Numbers correspond to those in Table II and Figure 7B.

Nos. 7, 10, and 11) show a rapid increase of permanent set starting at the yield point and a predominance of permanent set at the breaking point, immediate elastic recovery and delayed recovery being nearly equal. The marked similarity in the relative magnitudes and in the actual values of the elongation components for the 3 samples is evidence that the recovery behavior obtained in this study is characteristic for viscose and is fairly independent of the structure of the samples tested. Differences in values (column 9, Table II) at 50% of the tenacity at break, however, are caused mainly by very rapid changes in this region. This also demonstrates the inadequacy of presentation by numerical data at selected points. It must be admitted, however, that other specimens of viscose whose properties are more markedly affected by significant differences in manufacturing processes or in previous history may exhibit larger differences in recovery than were observed here.

Recovery of the two acetate (Nos. 16 and 17) and Vinyon N (Nos. 19 and 20) samples indicates that the behavior of these materials is similar to the recovery of viscose, despite some differences in breaking tenacities and extensibilities. Acetate shows a higher permanent set at the breaking point than viscose, and delayed recovery is predominant in the recoverable part of the Vinyon N samples at the breaking point. Comparison of the multifilaments with the staple yarns corroborates the observation made on viscose—namely, that the magnitude and shape of the three areas for recovery in the rectangular graphs of the multifilaments and staple yarns are very similar and that corresponding values of recovery in Table II are also in good agreement except when compared at 50% of the tenacity at break.

E. Nyon 300, Orlon Acrylic Fiber, and Fiber V **

Nylon 300 (No. 18), a strong and extensible fiber, is remarkable for its high actual value of total recovery (16.8%) and, consequently, for its low permanent set (6.5%) at the breaking point (Table III). Nylon has the lowest permanent set of the significantly extensible fibers tested (28% of the total elongation at break, Table II). Only Vinyon CF-HST (No. 15), wool (No. 21), and polyethylene A (No. 25) are comparable to nylon with respect to high extensibility and low permanent set, but these fibers have much lower tenacities. The immediate elastic recovery of nylon is not unusually high, the actual value being 4.2% at the breaking point, which corresponds to only 25% of its total recovery and 18% of its total elongation (Table V). Its delayed

* Fiber V is a Du Pont experimental fiber [3, 5]. It is now designated as "Dacron polyester fiber," and the fiber of the same chemical composition is known in Great Britain as Terylene [10].

recovery of 12.6%, however, is high, corresponding to 75% of its total recovery and 54% of its total elongation at the breaking point. Nylon does not have the disadvantages of poor extensibility, which characterizes other strong and elastic fibers, such as Fiberglas and Fortisan. From the molecular standpoint, nylon consists of a series of short hydrocarbon springs united by strong cross-linkages. These are responsible for the high recovery and low permanent set since they prohibit significant slippage of the long-chain molecules.

The recovery of nylon as compared to Orlon acrylic fiber (No. 12) [23, 32] and Fiber V (No. 13) may be of some interest since these are relatively new synthetic fibers of high quality. Graphs Nos. 12, 13, and 18 of Figure 7B represent the recovery behavior of the fibers and show the progressive increase in both extensibility and tenacity from Orlon acrylic fiber to Fiber V to nylon 300. The first two fibers exhibit similar recovery, markedly different from the behavior of nylon. This is demonstrated in Table V, where the actual as well as the relative values of recovery data for the 3 fibers at the breaking point are shown. It should be noted that Orlon acrylic fiber and Fiber V differ from nylon in that their actual values for immediate elastic recovery, delayed recovery, and total recovery (3a, Table V) are lower. The relative values of delayed recovery and total recovery expressed as percentages of the total elongation (3b) are nearly the same for these two fibers and are considerably lower than the corresponding values for nylon.

The extremely high delayed recovery of nylon contributes to seam puckering frequently observed when nylon threads are used [14, 36, 37]. Puckering is due in part to the tendency of nylon to creep back after being elongated in the stitching process. The difficulties encountered can be overcome to a certain extent by reducing the extensibility of nylon, but they cannot be entirely eliminated thereby. Fiber V has been shown to be superior to nylon in sewability [36]. This is due partly to the fact that the actual as well as the relative values of delayed recovery are markedly lower for Fiber V than for nylon. In addition, Fiber V, with a higher "modulus of elasticity"—as is clearly shown by the steep initial part of the stress-strain curve (Figure 6)—is less elongated than nylon by a given stress in the sewing operation. This comparison indicates that an excess of delayed recovery is undesirable for this particular application. The cause of sewing difficulties is still an open question because of the complexity and severity of this process. In sewing, both thread and fabric are subjected to high strain rates and high temperatures. However, consideration of recovery may help to solve some of the controversial problems involved.

F. Vinyon CF-HST

The recovery behavior of Vinyon CF-HST (No. 15) is remarkable for its similarity to nylon, having a low permanent set, high recovery, and especially high delayed recovery. Although the extensibility and breaking tenacity of Vinyon CF-HST are fairly high, they are not as high as those of nylon.

G. Vinyon NOZZ and NORU

Vinyon NOZZ and NORU are copolymers chemically different from Vinyon CF-HST; therefore, no correlation of their tensile properties was made.

The shrink-resistant Vinyon NORU (No. 20) was extended about 1300% and then heat-treated without tension at 135°C [4, 19]. This sample shows a somewhat lower tenacity and higher extensibility than Vinyon NOZZ (No. 9), which was extended to the same amount, but was not heat-stabilized and therefore not made shrink-resistant. Relative values of the elongation components are similar for both fibers at comparable levels of strain, but are quite different when compared at the same stress values. The permanent set of Vinyon NORU begins, however, at a lower strain and stress according to the lower yield point of this sample (Figures 6 and 7B).

H. Wool

The high "elasticity" of wool is one of the most important differences between this and other textile fibers and is responsible for the characteristic "softness" or "hand" of woolen fabrics. Wool (No. 21) has a higher extensibility than any other natural fiber tested. These valuable properties are produced partly by the peculiar morphology of wool fibers (scales and crimp) and partly by the inherent properties of the wool substance. Wool fibers consist of polypeptide chains held together by salt linkages, cystine linkages, and hydrogen bonds. The high recovery of wool is produced by strong cross-linkages and by the flexibility of the long-chain molecules.

In unextended fibers these molecules are coiled, and they are uncoiled as the fibers are stretched. The cross-links remain unbroken during this process and they prevent the chain molecules from slipping completely over each other. They assist greatly in the restoration of the initial structure after stress is removed. Only a minor portion of the high total recovery of wool (Table III) was found to be immediately recoverable at the breaking point. As in nylon 300, most of the total recovery consists of delayed recovery. This similarity can be understood from the resemblance of their molecular structure.

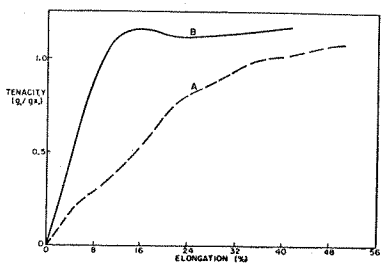

FIG. 8. *Stress-strain curves of polyethylene.*

I. Casein

The extensibility and tenacity of the man-made protein fiber casein (Nos. 22 and 23) are very similar to wool. The recovery of casein fibers remains, however, markedly below the excellent recovery of wool, and a large portion of the high total elongation at the breaking point is permanent set (Table III).

Raw and stabilized casein multifilaments have not only almost the same breaking tenacity and total elongation at break, but also their recovery behavior is similar. Stabilization by formaldehyde has little effect on the tensile properties in the dry state.

J. Polyethylene

Polyethylene A (No. 25) and B (No. 24) were obtained from the same base material, polyethylene C, by a cold drawing process in which they were stretched nearly 600%. Type A was then relaxed 10% to 12% to increase its shrink-resistance [13]. This process is known as controlled shrinkage. Type B received no such treatment and thus was more highly oriented but less shrink-resistant.

The somewhat higher tenacity and lower extensibility of Type B are to be expected in view of the higher orientation of this sample. Although the stress and strain values are fairly close together at the breaking point, the relationship between stress and strain is very different for both types. This is illustrated by the two stress-strain curves in Figure 8. The distinct yield point of Type B at a relatively high stress value is remarkable. A considerable difference exists in the recovery of both types as a result of their history. Actual values of immediate elastic recovery at the breaking point for both samples are relatively high and similar. Immediate elastic recovery increases at the very beginning of the stretching process until in the neighborhood of the yield point a maximum of nearly 80% of the actual total elongation is reached (Figure 7B). Then it decreases steadily to 10% at the breaking point. In contrast to this, the delayed recovery and permanent set of both samples are different. Type B does not show the previously described constancy of delayed recovery which was found for all the other fibers tested. At the breaking point the delayed recovery of Type B is markedly lower than that of Type A (Table II). The permanent set of Type B starts at a higher stress and strain by virtue of the high yield point. However, at higher strain values the permanent set of Type B markedly exceeds that of Type A when compared at the same level. Higher permanent set values for highly oriented polyethylene are contradictory to any experience with oriented fibers of viscose or acetate since the alignment of long particles makes further orientation impossible, strengthens the fiber, and thus prevents slippage, or permanent set, and reduces extension.

This unusual behavior of polyethylene is explained by the x-ray diffraction patterns of both samples shown in Figure 9. They reveal the following facts:

1. Both types are highly crystallized since they give distinct x-ray diffraction patterns.

2. The proportion between the crystalline and amorphous parts is nearly the same in both samples because the relative intensity of the diffraction spots and of the "amorphous ring" is not markedly different.

3. The orientation corresponds in both samples to the fiber axis or to the [001] direction of the crystal

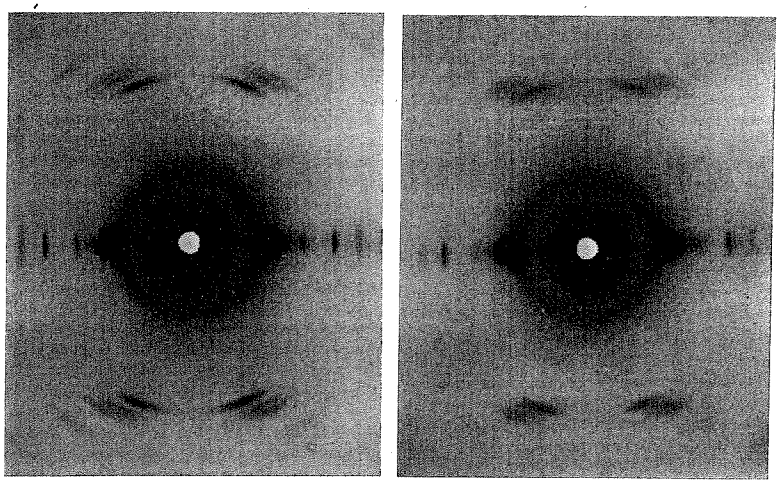

FIG. 9. *X-ray diffraction patterns of polyethylene. Type A—Left. Type B—Right.*

lattice. This is important since orientation along the [011] axis has also been observed in stretched polyethylene after relaxation [8] and this could affect markedly the tensile properties of such a fiber.

4. The degree of orientation is high and similar for both samples.

5. The crystalline part of Type B shows lattice defects, as indicated by the fuzziness of the diffraction spots, whereas no lattice distortion is observable on the clear x-ray diagram of Type A. The defects are a result of the cold drawing process. It is known that other cold-drawn materials, such as metals, show local displacement of atoms and formation of internal spaces, observable by the fuzziness of the x-ray pattern. Similar "destruction" of the crystal lattice during the stretching process was recently described [24] for nylon 300, when the yield point was exceeded (at an elongation of approximately 15%). It appears as a broadening of the diffraction lines on the x-ray diagrams of highly extended fibers, which can be interpreted as inhomogenous lattice defects or as decreased particles. Analogous observations have been made on metals at small plastic strains. The distortion of the crystal lattice is eliminated by the described controlled shrinkage of Type A, probably effectuated by moderate heating, by permutoid swelling, or by both. This procedure is analogous to the recrystallization of metals by annealing, where internal stresses are removed by heat treatment.

The x-ray diagrams of polyethylene A and B reveal that the main difference between the 2 samples is the presence of lattice defects in Type B. This explains the unusual recovery behavior and high permanent set of the highly oriented Type B, since structural defects and internal spaces intensify the slippage when stress is applied and this is always connected with a nonrecoverable elongation, or permanent set.

X. Comparison of Results with Those of Previous Investigators

Recovery data obtained in this study can be compared with data of other authors, such as Meredith, Maillard and coworkers, and Hamburger, only to a limited degree.

A. Meredith (1945)

Meredith [30] measured the recovery behavior of many single fibers from the beginning of stress up to

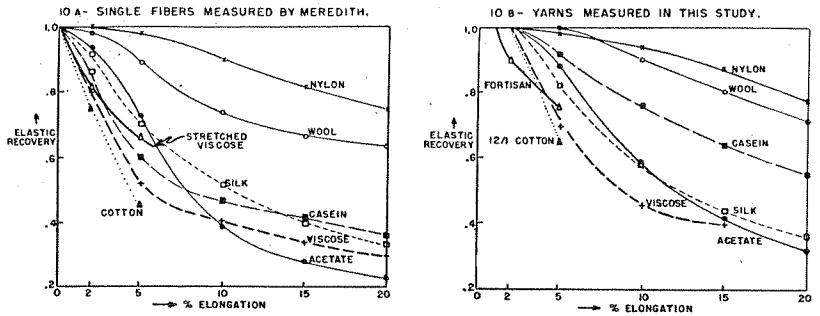

FIG. 10. *Recovery-strain curves of various filaments.*

rupture. He demonstrated the correlation between "elastic recovery" and stress or strain by means of "elasticity stress" and "elasticity strain" curves. "Elastic recovery" is the ratio of recoverable elongation to total elongation. It is closely related to the term "total recovery" (T.R.) used in the present study, which is the sum of immediate elastic recovery (I.E.R.) and delayed recovery (D.R.) when these are expressed as percentages of the actual total elongation:

$$\text{Elastic recovery} = \frac{\text{T.R.}}{100} = \frac{\text{I.E.R.} + \text{D.R.}}{100}.$$

The elastic recovery of acetate multifilament (No. 16), for example, as demonstrated in Table II and Figure 7B, is 1.00 at 50% of the tenacity at break, 0.58 at 50% of the total elongation at break, and 0.30 at the breaking point, since the values for immediate elastic recovery and delayed recovery are shown as 74% and 26%, 26% and 32%, and 14% and 16%, respectively, in columns 9, 10, and 11 of Table II. These data are higher (especially at 50% of tenacity) than Meredith's values for the acetate single fibers Seraceta (3.9 grex) and Celanese (1.1 grex). Besides some possible differences in the samples, variations in loading techniques might be responsible for this discrepancy.

Despite considerable differences in the two techniques used and in the samples tested, it is worthwhile to compare Meredith's results with the present recovery data since in both investigations many materials possessing widely different properties were tested.

In Figure 10A Meredith's data of "elastic recovery" for nylon, wool, casein, silk, viscose, acetate, stretched viscose, and cotton are plotted against strain. The data are taken from Table VIII of Meredith's paper [30] and represent average values obtained on single fibers at 2%, 5%, 10%, 15%, and 20% total elongation. In Figure 10B recovery-strain curves are demonstrated for the corresponding yarns as obtained directly from the upper rectangular graphs Nos. 18, 21, 22, 14, 10, 4, 16, and 5 of Figure 7B. Meredith's curves for viscose, stretched viscose, and cotton have been correlated to multifilaments of high-tenacity viscose (No. 10), high-tenacity Fortisan (No. 4), and 12/1 cotton staple yarn (No. 5), respectively, since their elongations at break are closest to the extensibility of Meredith's samples. The two sets of recovery curves in Figures 10A and 10B show that the agreement is surprisingly good between Meredith's data and those in the present paper, despite marked differences in the tests. Meredith's "elastic recovery" values are generally lower than ours, particularly at 2% elongation. This deviation can be explained by the differences in the loading technique.* The discrepancy between the two casein curves is most likely caused by differences in the properties of the samples tested.

* In Meredith's test a lower jaw speed was used. The samples were held extended 30 sec., and only 60 sec. relaxation time was allowed for recovery. All these factors increase the "permanent set" and decrease the "elastic recovery" as compared to the conditions of our tests (immediate removal of elongation and 300 sec. relaxation time). Consequently, an "elastic recovery" of 1.00 was observed for most fibers at 2% elongation in our tests.

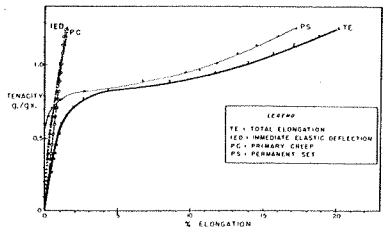

FIG. 11. *Stress-strain curves of acetate multifilament 300/104/1.5. (Measured by W. J. Hamburger.)*

The exceptional high recovery of nylon, the similarity of nylon and wool, and the inferiority of casein to wool with respect to recovery are also shown by Meredith's curves. However, no information is provided by these tests on the "quality" of the recovery since no differentiation was made between immediate and delayed recovery.

B. Maillard and coworkers (1947–48)

Seven of the fibers tested in this study were also investigated by Maillard and coworkers [26, 27]: cotton, regular and high-tenacity viscose, silk, acetate, nylon, and wool. The agreement between the results for total recovery at the breaking point is fairly good. The insignificant deviations are probably due to differences in the testing methods or in the inherent properties of the samples tested.

C. Hamburger (1948)

Some data of immediate elastic recovery and delayed recovery obtained in this study can be compared to those of "immediate elastic deflection" and "primary creep" of Hamburger [20, 21]. Despite the marked difference between the pulse-propagation technique and the repeated-loading technique, and also between the methods of evaluation, Hamburger's data for viscose, acetate, and nylon are similar to ours.

It is worth-while to demonstrate data obtained on acetate multifilaments by the pulse-propagation technique and by the repeated-cycling method used in the present study for purposes of comparison, even though the samples tested were different.

The values demonstrating the visco-elastic behavior of 300/104/1.5 Tennessee Eastman acetate

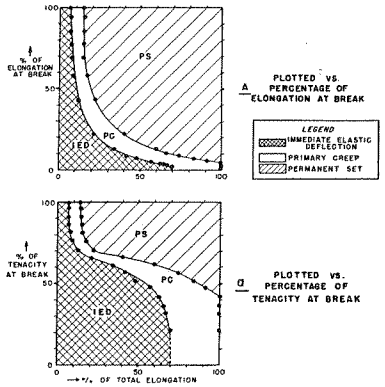

FIG. 12. *Quadratic graphs showing elongation components of acetate multifilament 300/104/1.5. (Measured by W. J. Hamburger.)*

multifilament as obtained by the pulse-propagation meter * are replotted in Figure 11, by means of four curves, and in Figures 12A and 12a, by means of two quadratic graphs.

These figures should be compared with Figures 4D, 5D, and 5d, which demonstrate the recovery data obtained in the present investigation on 100/40/2.5 Acele, Du Pont acetate multifilament (No. 16), using sustained elongation instead of the normal, immediate removal of elongation. This variation of our test conditions corresponds nearly to the conditions of Hamburger's tests, in which the immediate elastic deflection and the primary creep were measured on the sixth loading cycle. It is known that repeated stressing and sustained elongation produce a similar effect on the tensile properties. Comparison of the two sets of curves and graphs shows that Hamburger's data of deflection components correspond fairly well to our elongation components. This good agreement between actual as well as relative values of the three components obtained by tests made on different samples using different testing methods proves that data of the three components are indeed representative of inherent fiber properties.

* These were presented by Hamburger in Graph 11c, p. 732, of his paper in TEXTILE RESEARCH JOURNAL [20] and were also shown in Figure 5, p. 496, of his condensed article in the *A.S.T.M. Standards* on Textile Materials [21].

Similar agreement was found for total recovery by Meredith [30], who compared his results with those of a large number of early investigations made on single fibers and yarns of cotton, silk, viscose, acetate, wool, and Lanital published between 1927 and 1943 by Shorter, Collins, Küsebauch, Saxl, Langer, Kurts, Böhringer, Schwab, Weltzien, and Loasby. This agreement also indicates that the recovery behavior of fibers is by no means as subject to variation in particular test conditions as was frequently believed.

XI. Summary

The cycling technique described makes it possible to obtain comparable data on the immediate and delayed recovery and the permanent set of textile fibers and yarns, and gives a more accurate characterization of tensile properties than the conventional stress-strain curve. The method as applied to measure the recovery behavior may have some inadequacies which will be eliminated by improved equipment. The recovery data obtained can serve as a basis for further investigations on fibers, yarns, and fabrics since they indicate the applicability of these textile materials for specific end-uses. The knowledge of recovery also provides a better understanding of the complex behavior of textile materials and their practical implications.

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